MUON AND FFAGS

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EXTINCTION OF NUCLEAR WASTE

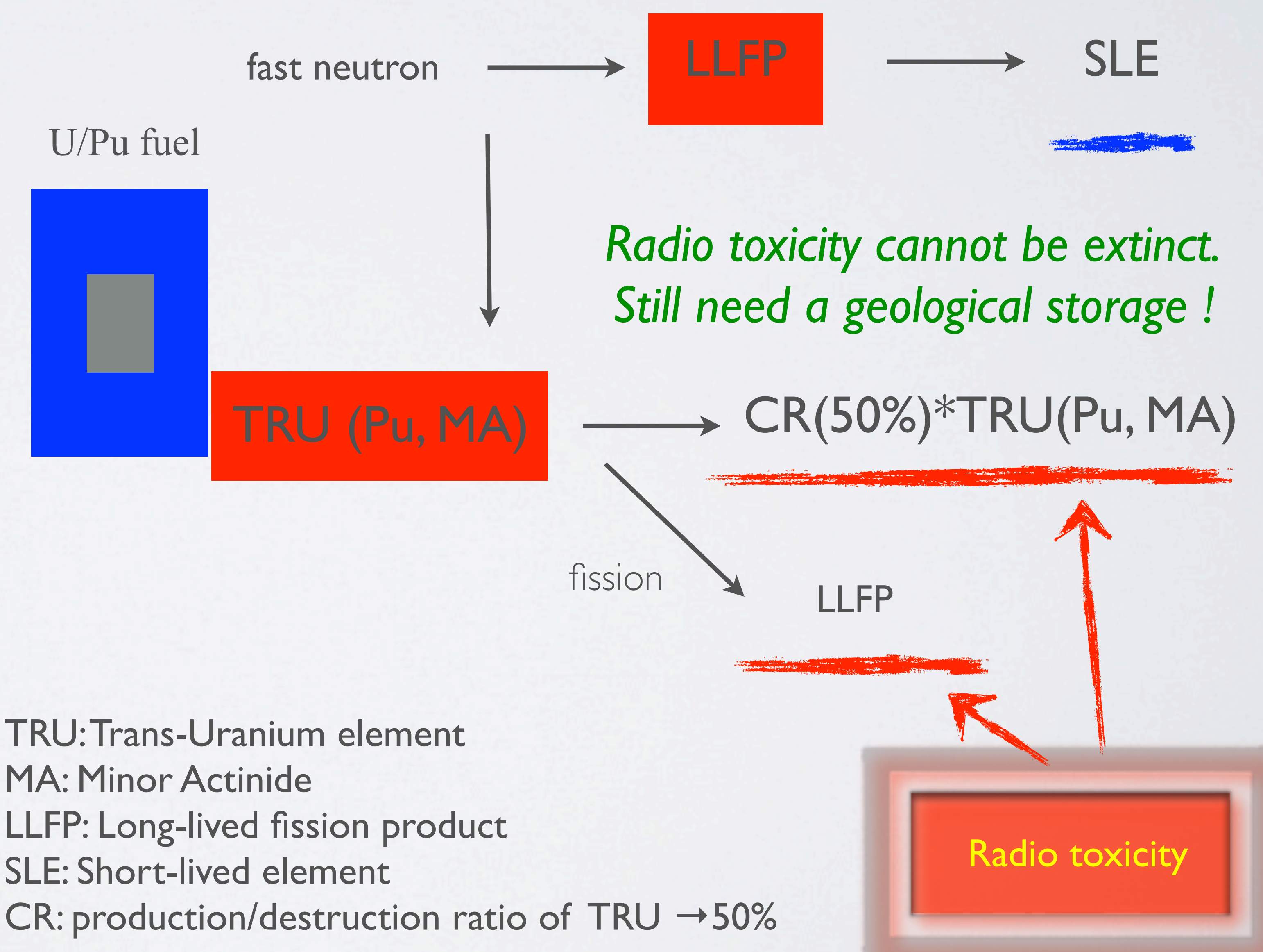
Is ADS/FR nuclear transmutation really useful?

- Fast neutron can reduce of long-lived nuclear toxicity. ADS/FR can provide fast neutrons.

- But, ADS/FR needs fissile nuclear fuels, U, Pu, Th, etc. ADS/FR can reduce but not completely.

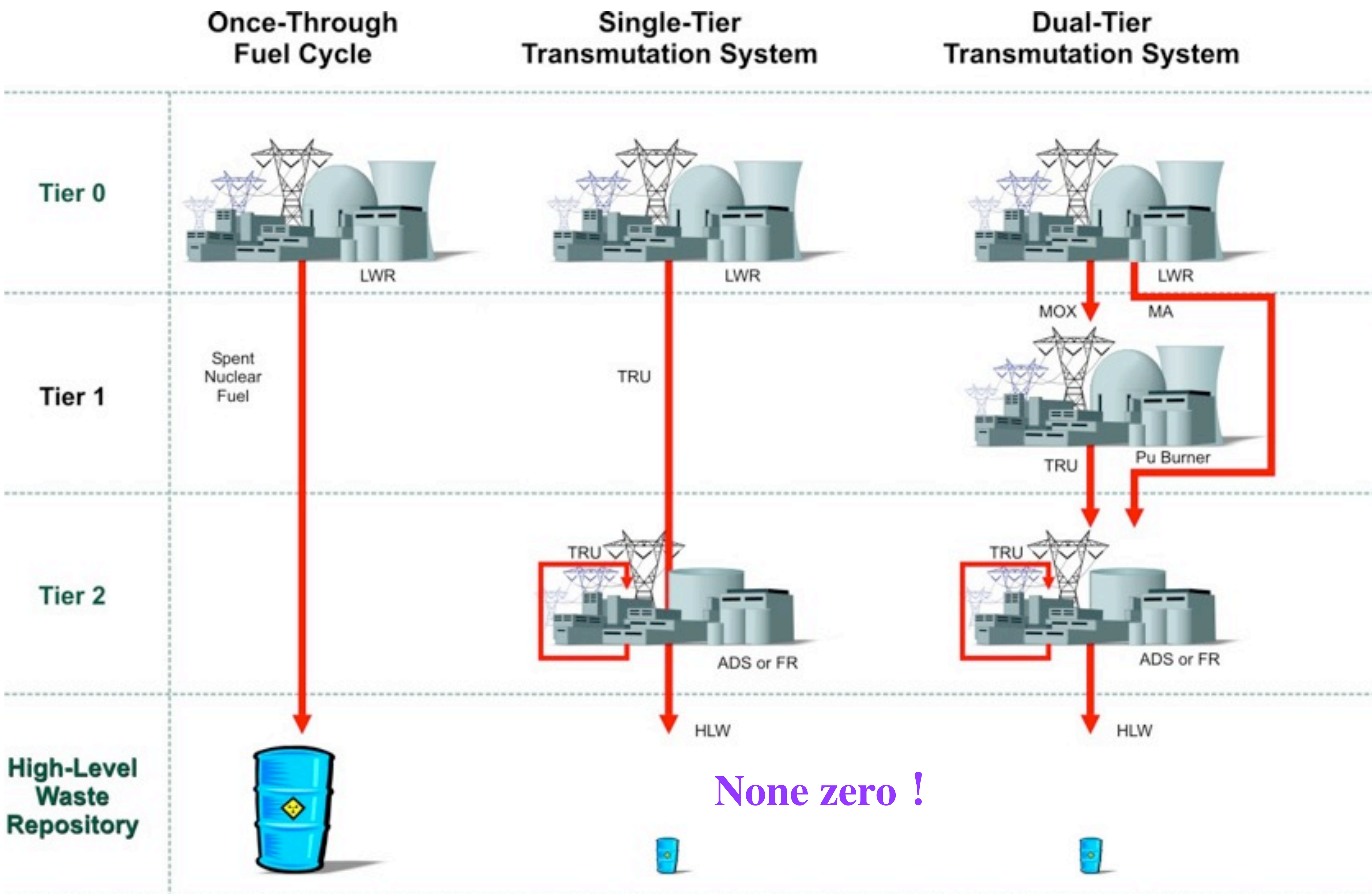
Still we need deep geological storages.

Difficult to get public consensas.



TRU: Trans-Uranium element
MA: Minor Actinide
LLFP: Long-lived fission product
SLE: Short-lived element
CR: production/destruction ratio of TRU →50%

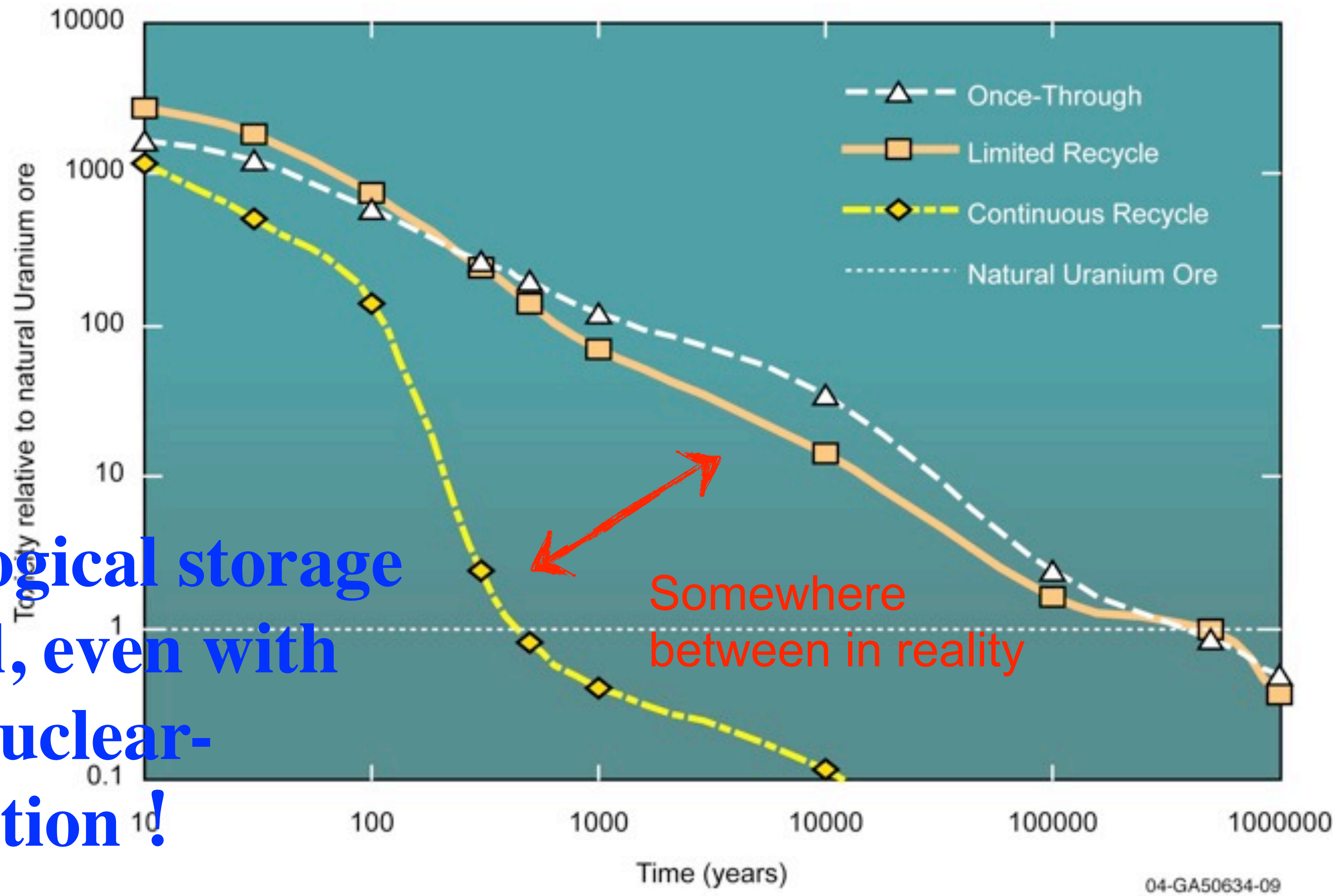
Transmutation System Approach



W.S.Yang :ANL , ws on App. of HIPA, Oct.19/2009,FNAL

FR or ADS recycling in reality

Waste Management Objective: Radiotoxicity Reduction



Deep geological storage is essential, even with FR/ADS nuclear-transmutation !

- **Continuous recycle required for significant reduction of radiotoxicity**
- **Continuous recycle strategy can significantly improve the basic nature of nuclear waste disposal (thermal load and isolation time frame)**

MUON NUCLEAR TRANSMUTATION μ-NTM

- Nuclear transmutation with **weak interaction**

$$\mu^{-} + p \rightarrow n + \nu_{\mu}$$

- Production of ^{99m}Tc :medical RI tracer→ very useful
  - ➡ μ-NTM proposed by **K.Nagamine.**

$$\mu^{-} + {}^{100}\mathrm{Ru} \rightarrow {}^{99m}\mathrm{Tc} + n$$

- 500MeV-3mA(1.5MW) proton driver (Cyclotron :Nagamine) can provide
  - ➡ 3.3×10^{12} μ/sec μ^{-}. → **1kCi-6days ^{99m}Tc** : Total consumption in Japan
- How about μ-NTM for nuclear wastes?

MUON NUCLEAR TRANSMUTATION μ-NTM

$\mu^- + p \rightarrow n + \nu_\mu$ 95% efficiency!

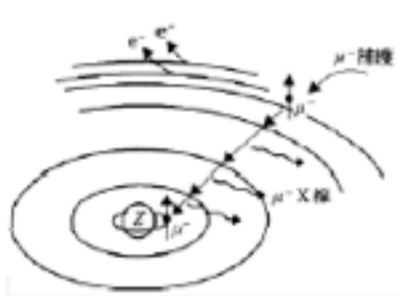
by K.Nagamine

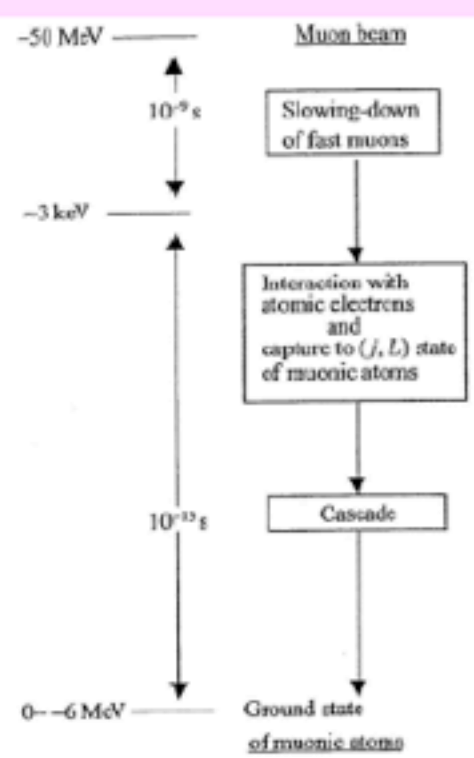
But, slow muons (<MeV/c) are needed.

物質中のμ-

ミュオン原子

重い電子





Nuclear transmutation with stopped negative muon

Phenomena taking place in the matter after stopping of "heavy electron" like negative muons;

1) Formation of excited states of small atom by penetrating electrons surrounding nucleus.

2) Transition within ns to the atomic ground state which has a radius of *270/Z*x10^{-13} cm for Z nuclei; In ^{100}Ru (Z=44) 6.13x10^{-13} cm.

3) Strong capture reaction of μ^- via weak interaction ($\mu^- + p \rightarrow n + \nu_\mu$) since atomic radius becomes comparable to the nuclear radius which is $1.2(A)^{1/3}$x10^{-13} cm; for ^{100}Ru, 5.37x10^{-13} cm. The nuclear capture process is competing with a free decay ($\mu^- \rightarrow e^- + \nu_\mu + \nu_e$); in ^{100}Ru (Z=44), nuclear capture is 95 % and free decay is 5 %.

4) After nuclear capture to highly excited (close to 100 MeV), particle (mainly neutron) emission takes place to produce a unique process of element transmutation.

Most of the stopping μ^- makes nuclear transmutation

2013年9月20日金曜日

EXTINCTION OF NUCLEAR WASTES WITH μ-NTM

- NTM based on FR/ADS can reduce radio-toxicity but not completely.
- μ-NTM convert TRU to U or less Z-element: Proton converts neutron with weak interaction.
  - Free from radio-toxicity perfectly!

NUCLEAR WASTES FROM NUCLEAR POWER PLANT

- Production of nuclear wastes from Uranium fuel (3% enriched U; 1ton @ 1GWe nuclear power plant, operation in 1 year
  - Pu 10kg
  - Pt 2kg
  - Short-lived FP 26kg
  - Long-lived FP 1.3kg
  - Minor Actinides (Np, Am, Cm) 0.6kg

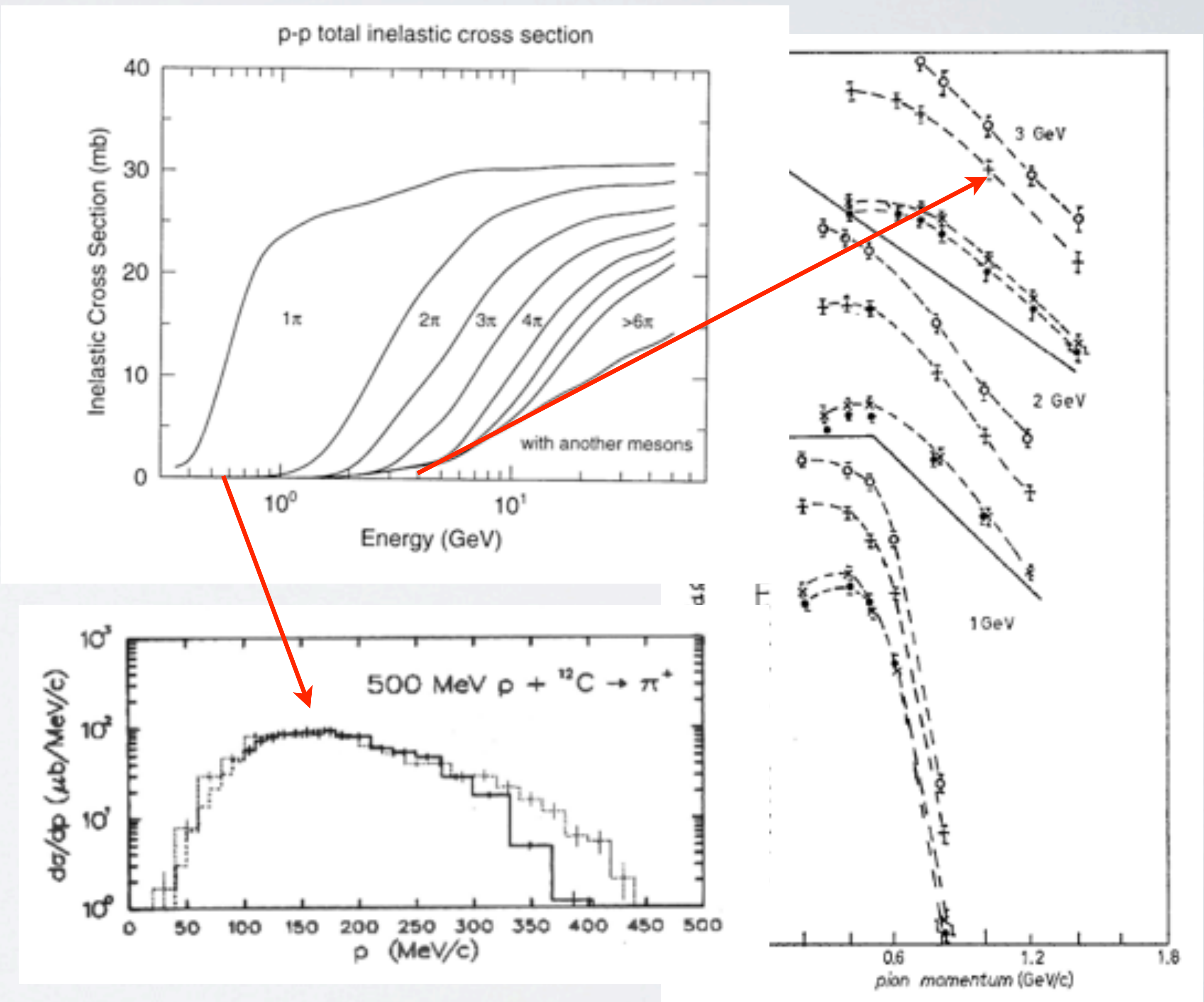
If μNT can treat LL-FP and MA with 2-4mol/year, a deep geological storage(GS) may not be necessary.
*ADS or FR cannot treat all MA and need GS.

← 4 mol/year！

- 1 GWe nuclear power plant for 40 years operation :
  - Nuclear fuel charging : 10tons/10years

PRODUCTION OF STOPPED NEGATIVE MUONS

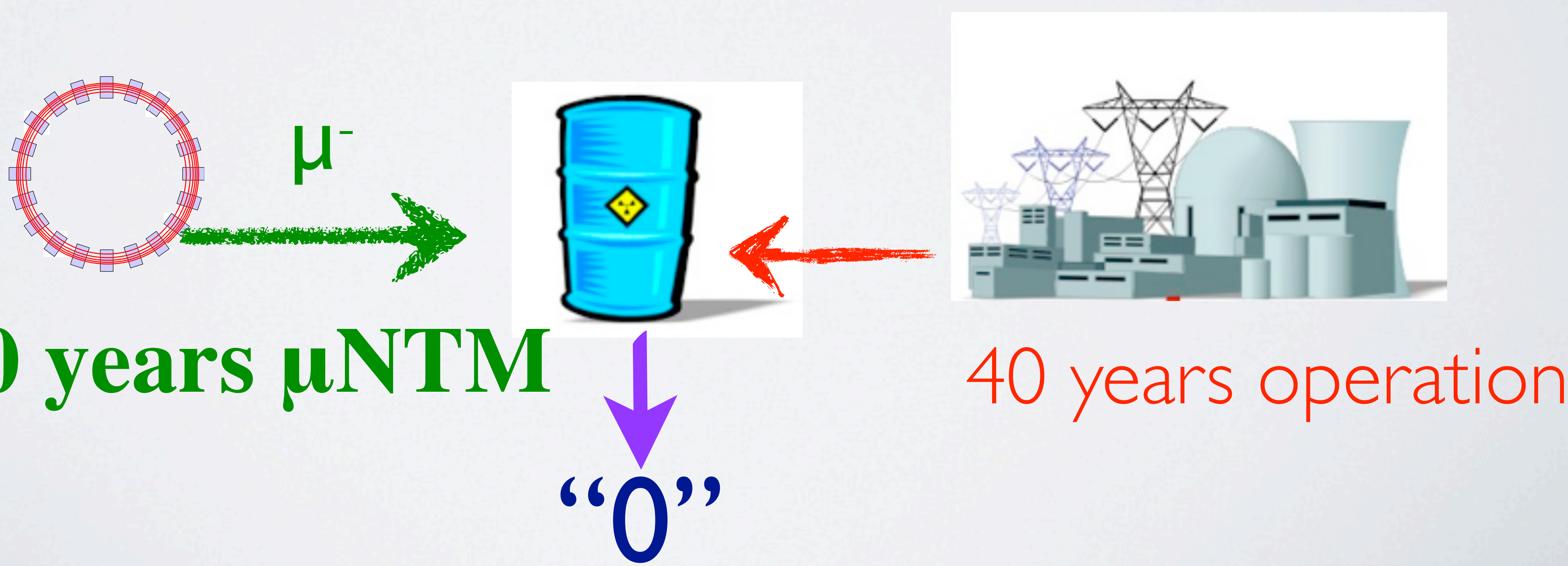
- To get stopped negative muons;
  - p(<500MeV)+n→p+π^- :Low energy proton
  - π^- (~200MeV/c) capture & degradation →MeV/c
  - $\pi^- \to \mu^-$ degradation & stopped.
- Difficulties:
  - Large dE/dx → thin target(10cm C)
  - Small cross section of π^- production ~mb
  - π^-/proton ~10^{-4} ← <10^{-3} times smaller than request!



MUON NUCLEAR TRANSMUTATION

μ-NTM

- Total LLFP and MA from 1GWe nuclear power plant for 40 years (lifetime) operation. → 160 mol.
- If μ-NTM can treat LL-FP and MP with 2mol/year, 80 years for complete extinction . → *Nice!*



NUMBERS OF STOPPED NEGATIVE MUONS REQUIRED FOR NUCLEAR WASTES TREATMENT

- Stopped μ^- intensity required to treat LLFP and MA with a rate of 2 mol/year,

  ➡ 2[mol] x NA / $\varepsilon(\mu^- + p \rightarrow n + \nu_\mu)$ ~ 1.2 x10^{24} [muons/year] = 3.8 x 10^{16} [μ^-/sec] :

    - cf. ~ 1 x 10^{12} (J-PARC） **x38,000！**

MUON YIELD

To get 3.8×10^{16} [μ^-/sec] with π^-/p>0.5 （Proton beam current : Ip>12mA cw)

- **Need thick enough pion production target : t ~100m ; σ=1mb @400MeV: x1000**
  - Ordinary π/μ production target → thickness ~10cm for E=500MeV

➡ Overcome the energy loss caused by stopping power

➡ Energy recovery → **“ERIT”**

- **Efficiency of muon capture > 0.5 : 6-D capture with strong magnetic field (B~2T): x10**
  - Energy of μ^- < 200MeV/c (ϱ<0.33m)

  ➡ Deuteron(proton) beam energy ~ 400MeV/u

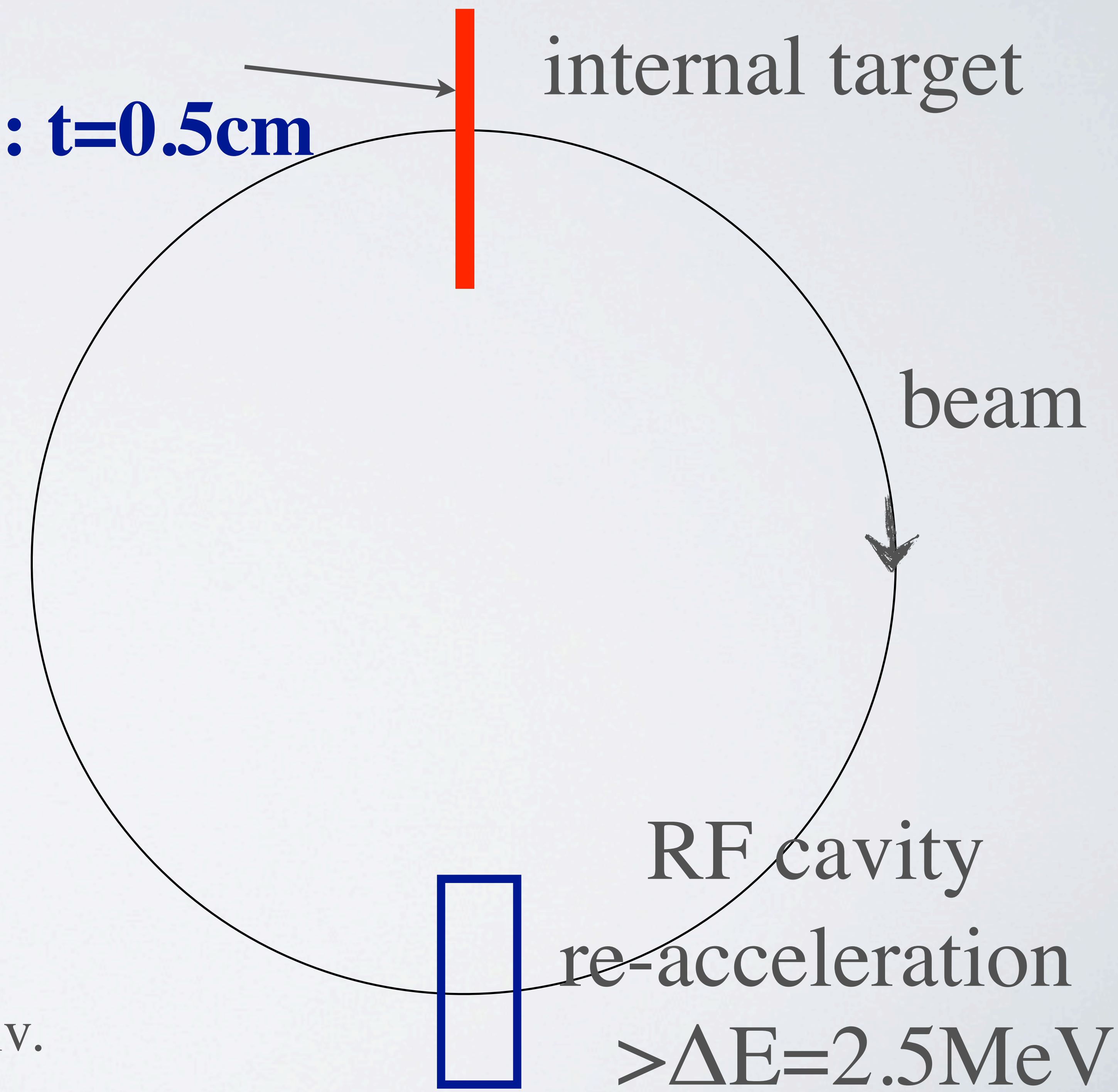
- **Proton driver beam power 4.8MW (400MeV -12mA) : x5**

ERIT FOR MUON PRODUCTION

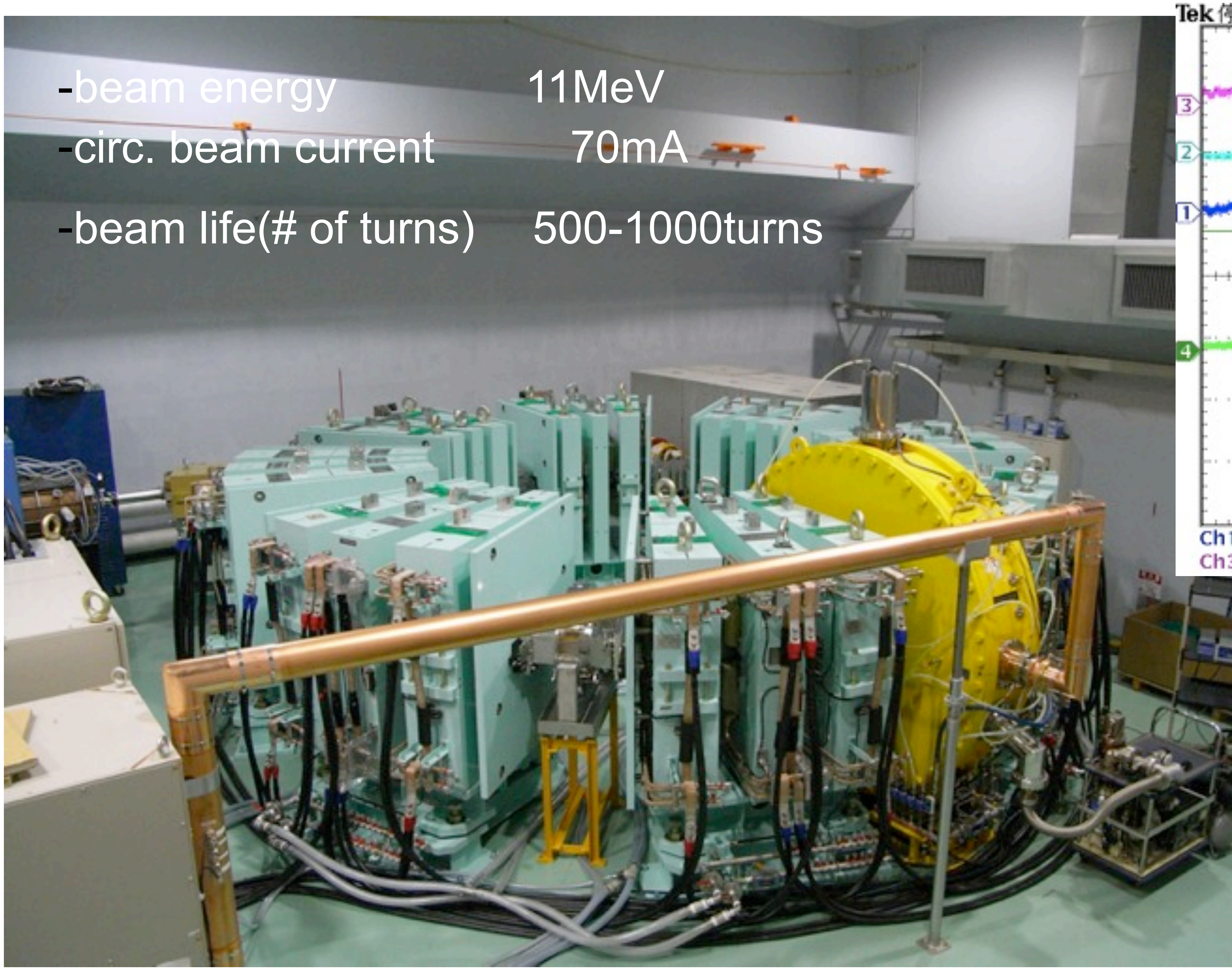
- ERIT:Emittance Recovery Internal Target in storage ring.
- Figure of merit
  - E threshold >300MeV/u
  - Energy recovering.

$$FOM = \frac{NL}{\int_{E}^{300\,MeV} \left({dE}/{dx} \right)^{-1} dE}$$

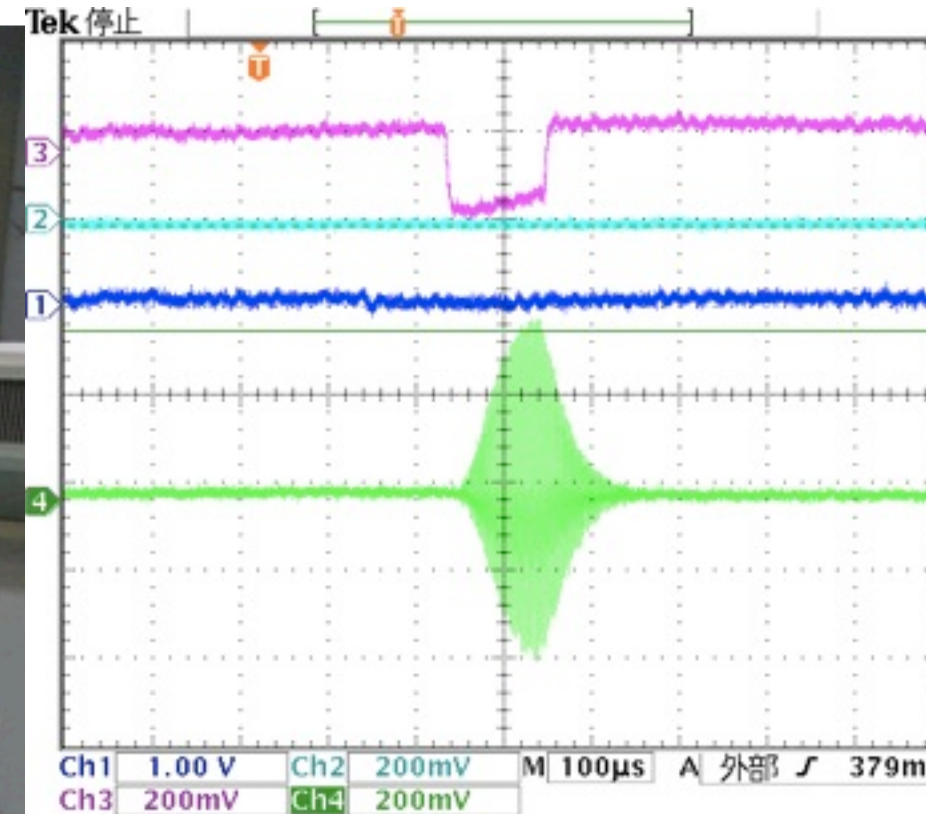
- 500MeV/u deuteron
  - <ε>rms ~ 462mm.mrad!
- ΔE~2.5MeV @0.5cm C
- N~20000 turns→100m target equiv.

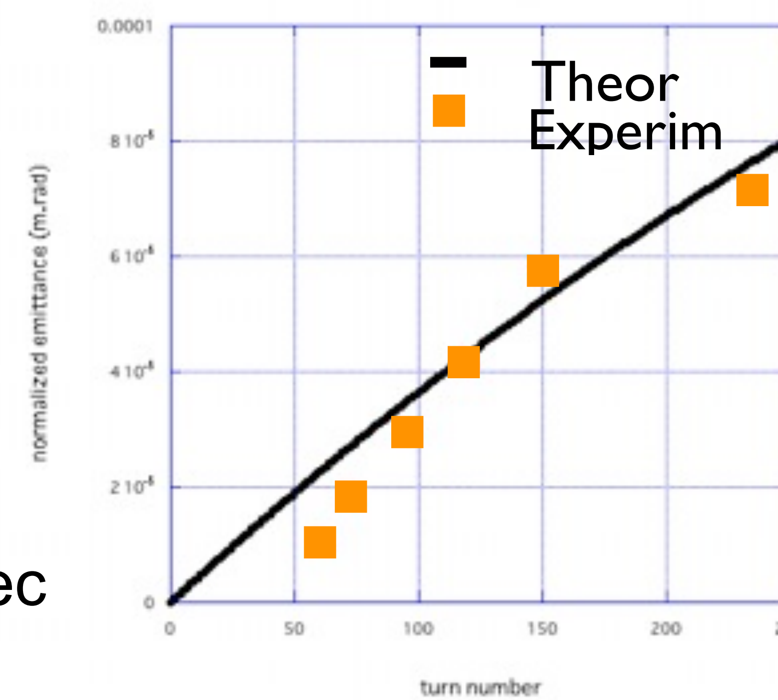


FFAG-ERIT RING



-beam energy 11MeV
-circ. beam current 70mA
-beam life(# of turns) 500-1000turns





-acceptance Av>3000mm.mrad, dp/p>+-5%(full)

$-\nu_x, \nu_y$ 1.77, 2.27

Neutron Yield > 10^{13}n/sec

μERIT -ERIT FOR MUON PRODUCTION

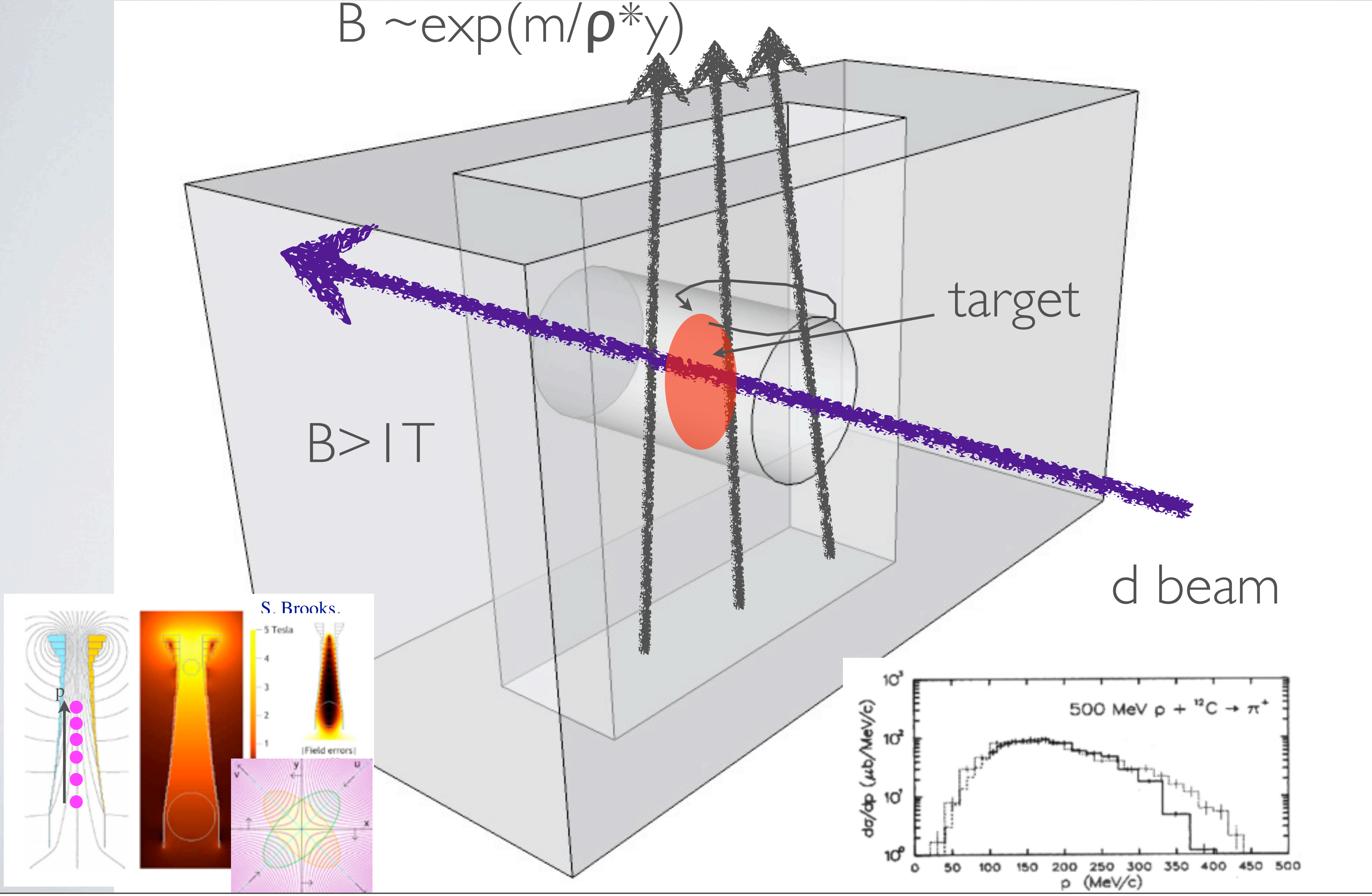
- Place a π-production target in the magnetic field.

  1. π capture and decay → Need high B (>1T) and distance.

  2. μ transport and degradation → Need high B(>1T) and material.

- V_FFAG looks interesting!

ERIT_V-FFAG


B ~exp(m/ρ*y)
target
B>1T
d beam
S. Brooks.
5 Tesla
|Field errors|
500 MeV p + 12C → π+
dσ/dp (μb/MeV/c)
p (MeV/c)
0 50 100 150 200 250 300 350 400 450 500

BETATRON MOTION AROUND CIRCULAR ORBIT

Eqs. of motion

$$\frac{d^2x}{d\theta^2}+\left[\frac{e}{p}B_y(\rho+x)-1\right](\rho+x)=0,$$

$$\frac{d^2y}{d\theta^2}-\left[\frac{e}{p}B_x(\rho+x)^2\right]=0.$$

Linearization

$$\frac{d^2x}{d\theta^2}+x+\frac{\rho}{B_0}\left[\left(\frac{\partial B_y}{\partial x}\right)x+\left(\frac{\partial B_y}{\partial y}\right)y\right]=0,$$

$$\frac{d^2y}{d\theta^2}-\frac{\rho}{B_0}\left[\left(\frac{\partial B_x}{\partial x}\right)x+\left(\frac{\partial B_x}{\partial y}\right)y\right]=0.$$

normal

skew

MAGNETIC FIELD FOR ZERO CHROMATICITY

(1) Ring

a)Normal:H-FFAG $\frac{R}{\rho} = const.\ \&\ \frac{R}{B_y}\left(\frac{\partial B_y}{\partial x}\right) = k \longrightarrow B_y = B_y^0\left(\frac{R}{R_0}\right)^k$

b)Skew:V-FFAG $R, \rho = const.\ \&\ \frac{\rho}{B_y}\left(\frac{\partial B_y}{\partial y}\right) = n \longrightarrow B_y = B_y^0\left(\frac{n}{\rho} y\right)$

(2) Straight line

a)Normal:H-FFAG $\rho = const.\ \&\ \frac{\rho}{B_y}\left(\frac{\partial B_y}{\partial x}\right) = n \longrightarrow B_y = B_y^0 \exp\left(\frac{n}{\rho} x\right)$

b)Skew:V-FFAG $\rho = const.\ \&\ \frac{\rho}{B_y}\left(\frac{\partial B_y}{\partial y}\right) = n \longrightarrow B_y = B_y^0 \exp\left(\frac{n}{\rho} y\right)$

V_FFAG :LINEAR MODEL

- Betatron equations of V_FFAG: x-y coupled.

$$\frac{d^2x}{d\theta^2} + x + ny = 0,$$

$$\frac{d^2y}{d\theta^2} + nx = 0.$$

- Normal mode: diagonalization

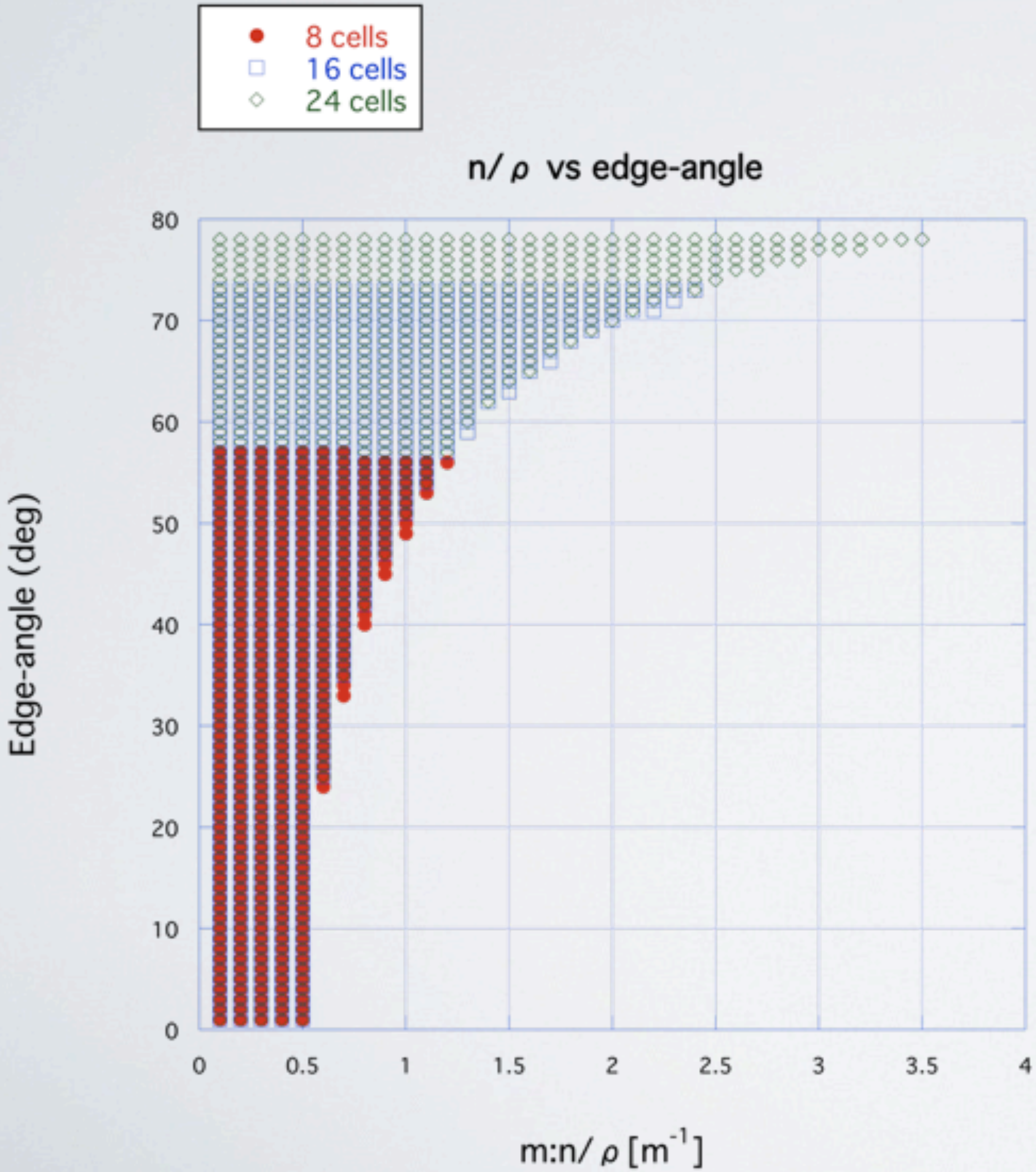
$$M = T^{-1}\begin{pmatrix} U & 0 \\ 0 & V \end{pmatrix} T, T = \begin{pmatrix} \mu I & SR^T S \\ R & \mu I \end{pmatrix}.$$

$$U = I\cos\psi_u + J_u \sin\psi_u,$$
$$V = I\cos\psi_v + J_v \sin\psi_v.$$

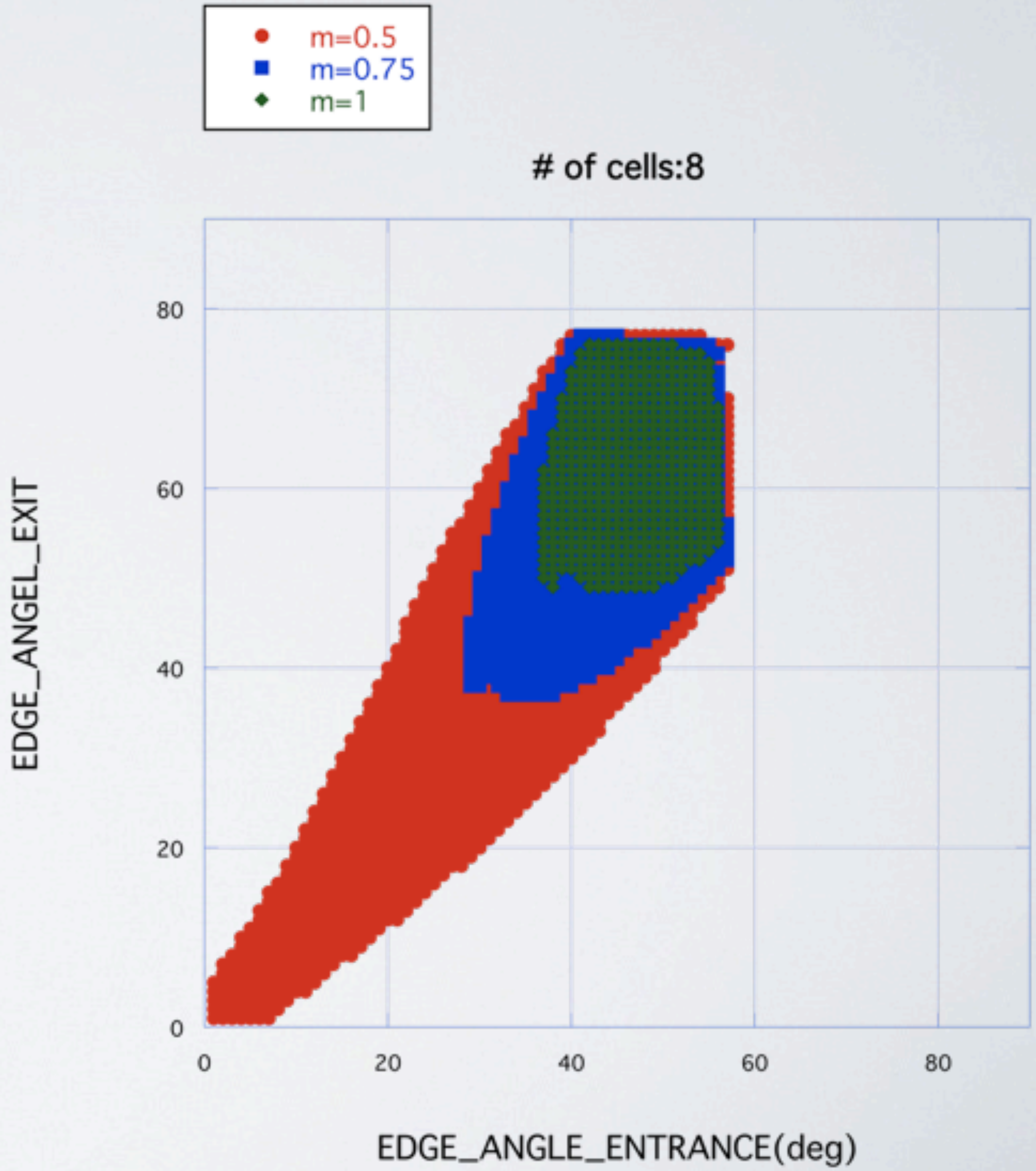
$$J_{u,v} = \begin{pmatrix} \alpha_{u,v} & \beta_{u,v} \\ -\gamma_{u,v} & -\alpha_{u,v} \end{pmatrix}.$$

STABILITY-AG FOCUSING

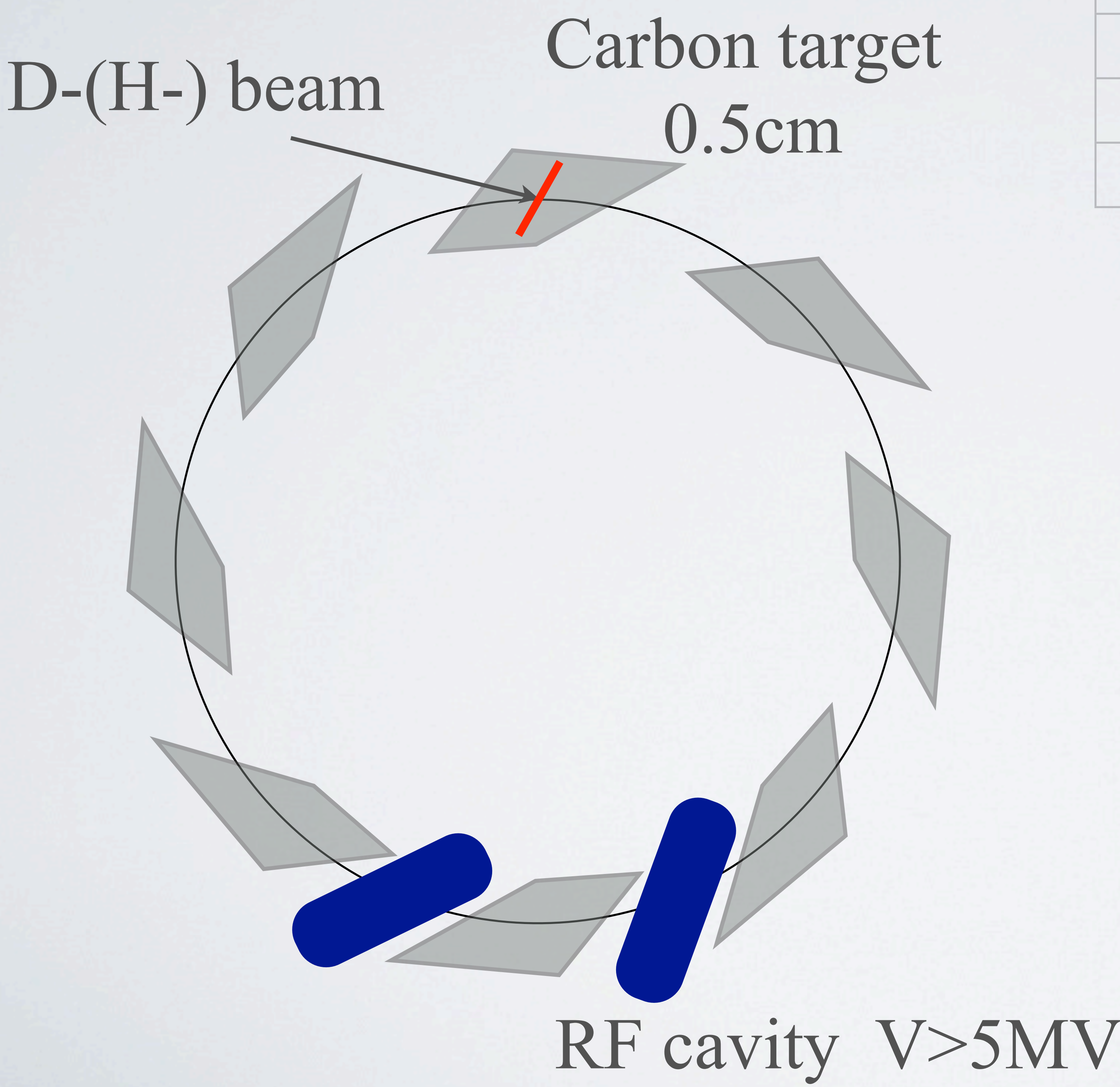
(1) m(=n/ρ) -edge angle ($\xi_{ent}=\xi_{ex}$)



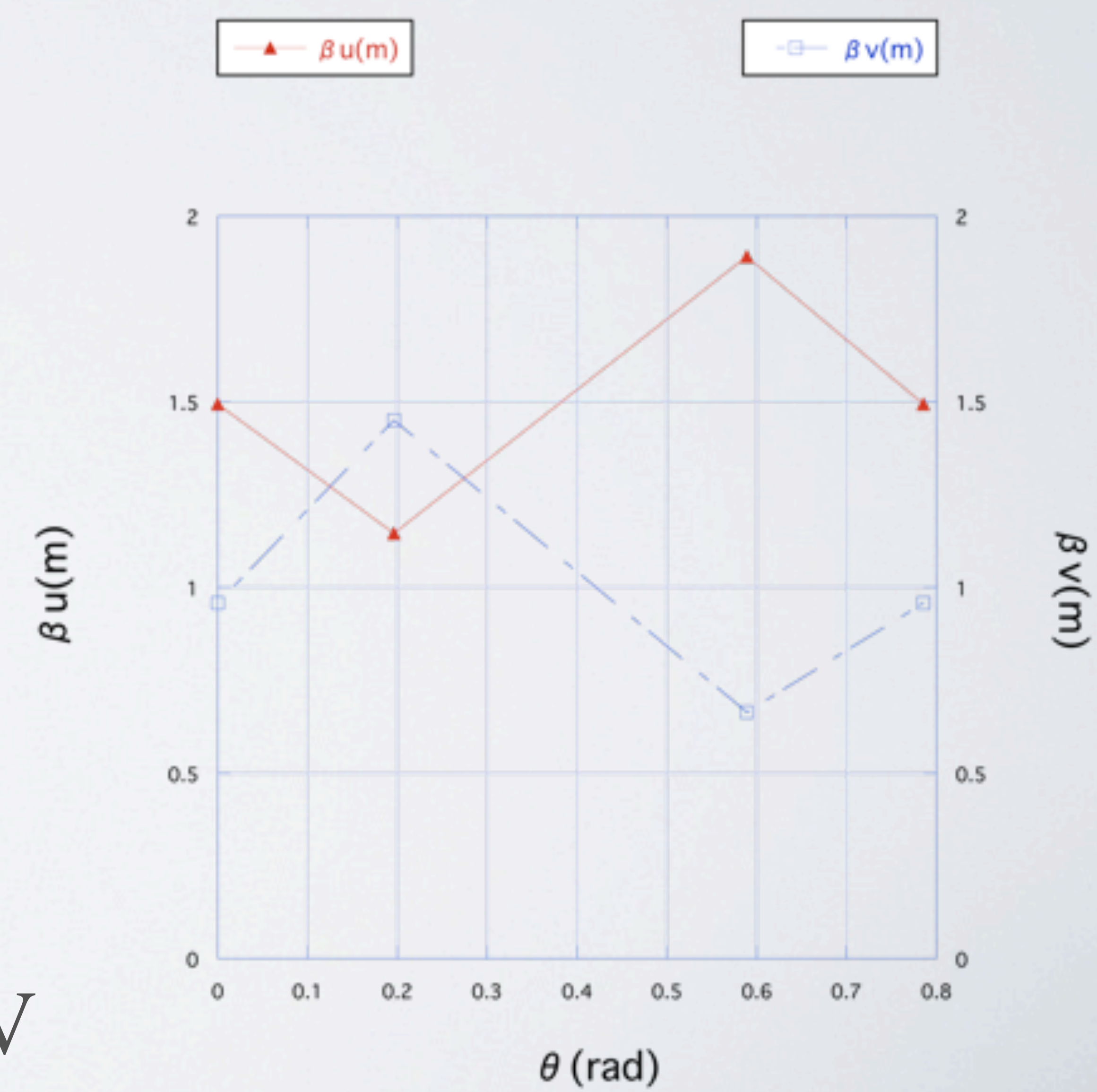
(2) ξ_{ent} - ξ_{ex} for 8-cell ring



μ-ERIT_v_FFAG



type	v_FFAG
energy	500[MeV/u]
numbers of cells	8
packing factor	0.5
m	0.5 [m-1]
radius	2(4) [m]
magnetic field	3.3[T]
edge angle (ent-ext)	50-50 [degree]



SUMMARY

- **Intense low energy muon source with ERIT using v_FFAG is proposed.**
  - Very long production target can be effectively realized with ERIT scheme, which is good for production of slow π-/μ-.
    - ➡ Efficiency x1000
  - π-/μ- are captured and transported by strong magnetic field of v_FFAG.
  - μ- yield ~ 1×10^{16} muons/sec
- **Technical (many) issues;**
  - Nuclear reactions (elastic scattering)
  - Target heating
  - Radiation (neutrons!)